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# Wind farm—A power source in future power systems

Z. Chen *, F. Blaabjerg

*Aalborg University, Institute of Energy Technology, Pontoppidanstraede 101, DK-9220 Aalborg East, Denmark*

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ABSTRACT

The paper describes modern wind power systems, introduces the issues of large penetration of wind power into power systems, and discusses the possible methods of making wind turbines/farms act as a power source, like conventional power plants in power systems. Firstly, the paper describes modern wind turbines and wind farms, and then introduces the wind power development and wind farms. An optimization platform for designing electrical systems of offshore wind farms is briefed. The major issues related to the grid connection requirements and the operation of wind turbines/farms in power systems are illustrated.



**Contents**



## 1. Introduction

Globally, wind power development is experiencing dramatic growth. According to the Global Wind Energy Council, GWEC, 15,197 MW wind turbine has been installed in 2006, an increase of 32% over 2005. The installation of the total global wind energy capacity is increased to 74,223 MW by the end of 2006 from

* Corresponding author. Tel.: +45 99 40 92 55; fax: +45 98 15 14 11.
*E-mail addresses:* zch@iet.aau.dk (Z. Chen), fbl@iet.aau.dk (F. Blaabjerg).
*URL:* http://www.iet.aau.dk

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59,091 MW of 2005. In terms of economic value, the wind energy sector has now become one of the important players in the energy markets, with the total value of new generating equipment installed in 2006 reaching US$23 billion or €18 billion [1].

Europe continues to lead the world in total installed capacity. In 2006, the country having the highest total installed capacity is Germany with 20,621 MW, Spain and the United States are in second and third place, each with a little more than 11,603 MW installed. India is in fourth place, and Denmark ranks fifth. Asia experienced the strongest increase in installed capacity outside of Europe, with an addition of 3679 MW, taking the total capacity over 10,600 MW, about half that of Germany. The Chinese market was boosted by the country's new Renewable Energy Law. China has more than doubled its total installed capacity by installing 1347 MW of wind energy in 2006, a 70% increase over 2005. This brings China up to 2604 MW of capacity, making it the sixth largest market worldwide. It is expected that more than 1500 MW will be installed in 2007. Growth in African and Middle Eastern market also picked up in 2006, with 172 MW of new installed capacity – mainly in Egypt, Morocco, and Iran – bringing the total up to 441 MW, a 63% growth.

The European Wind Energy Association (EWEA) has set a target to satisfy 23% European electricity needs with wind by 2030. The exponential growth of the wind industry reflects the increasing demand for clean, safe and domestic energy and can be attributed to government policies associated with the environmental concerns, and research and development of innovative cost-reducing technologies.

The large scale development of wind power results in the wind turbines/farms becoming a significant part of the generation capacity in some area, which requires that the power system treats the wind turbines/farms like a power source, not only an energy source. The wind power penetration would result in variations of load flows in the interconnected systems, as well as re-dispatch of conventional power plants, which may causes the reduced reserve power capacity. Some actions become necessary to accommodate large scale wind power penetration. For example, the electric grid may need an expansion for bulk electricity transmission from offshore wind farms to load centers, and it may require reinforcement of existing power lines or construction of new power lines, installation of Flexible AC Transmission system (FACTs) devices, etc.

This paper will discuses the important issues related to the large scale wind power integration into modern power systems as a new type of power stations. Firstly, the modern wind turbines and wind farms will be described; the wind power development and wind farms in Denmark will be introduced. An optimization platform for designing electrical system of offshore wind farms is presented. The impacts of wind farms on power system are analyzed, then the technical requirements for wind farm grid connection will be introduced. The possible operation and control methods to meet the specifications are discussed.

## 2. Modern wind power systems

### 2.1. Modern wind turbines

The electrical power produced by wind turbine generators has been increasing steadily, which directly pushes the wind technology into a more competitive area. Basically a wind turbine consists of a turbine tower, which carries the nacelle, and the turbine rotor, consisting of rotor blades and hub. Most modern wind turbines have three rotor blades usually placed upwind of the tower and the nacelle. On the outside the nacelle is usually equipped with anemometers and a wind wane to measure the wind speed and direction, as well as with aviation lights. The nacelle contains the key components of the wind turbine, e.g. the gearbox, mechanical brakes, electrical generator, control systems, etc. The wind turbines are not only installed dispersedly on land, but also combined as farms with capacities of hundreds MWs. Which are comparable with modern power generator units, consequently, their performance could significantly affect power system operation and control. The main components of a modern wind turbine system are illustrated in Fig. 1, including the turbine rotor, gear box, generator, transformer and possible power electronics.

The conversion of wind power to mechanical power is done aerodynamically. The available power depends on the wind speed but it is important to be able to control and limit the power at higher wind speed to avoid damage. The power limitation may be done by stall control (the blade position is fixed but stall of the wind appears along the blade at higher wind speed), or active stall (the blade angle is adjusted in order to create stall along the blades) or pitch control (the blades are turned out of the wind at higher wind speed), which result in power curves as shown in Fig. 2.

Mainly three types of typical wind generator systems exist [2]. The first type is a constant-speed wind turbine system with a standard squirrel-cage induction generator (SCIG) directly connected to the grid. The second type is a variable speed wind turbine system with a doubly fed induction generator (DFIG). The power electronic converter feeding the rotor winding has a power rating of approximately 30% of the rated power; the stator winding of the DFIG is directly connected to the grid. The third type is a variable speed wind turbine with full-rated power electronic conversion system and a synchronous generator or a SCIG. A multi-stage gearbox is usually used with the first two types of generators. Synchronous generators, including permanent magnet generator, may be direct driven, though a low ratio gear box system, one or two stage gearbox, becomes an interesting option.

The suitable voltage level is related to the amount of power generated. A modern wind turbine is often equipped with a transformer stepping up from the generator terminal voltage, usually a voltage below 1 kV, to a medium voltage around 20 kV or 30 kV, for the local electrical connection within a wind farm. If the wind farm is large and the distance to the grid is long, a transformer may be used to further step up the medium voltage in

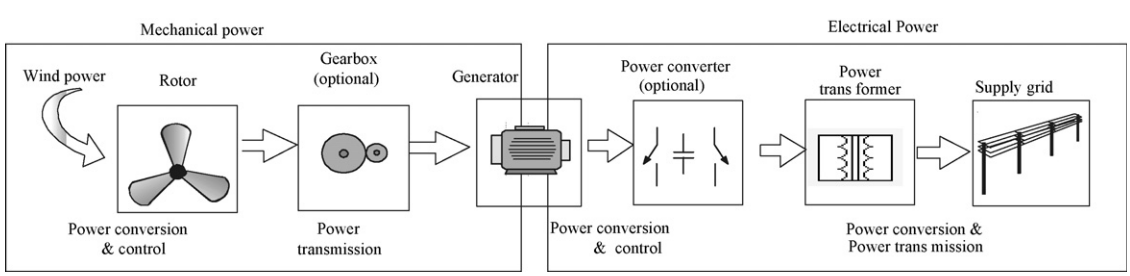



**Fig. 1.** Main components of a wind turbine system.

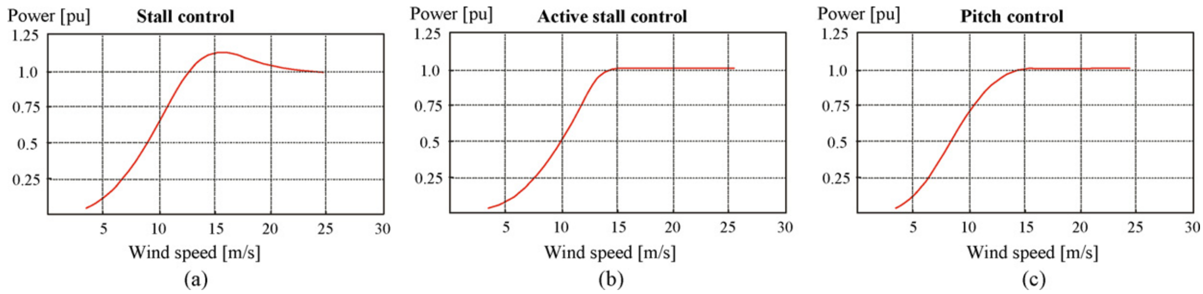



**Fig. 2.** Power characteristics of fixed speed wind turbines (a) stall control (b) active stall control (c) pitch control.

the wind farm to a high voltage at transmission level. For example, for large onshore wind farms at hundreds of MW level, high voltage overhead lines above 100 kV are normally used. For offshore wind farms with a long distance transmission to an onshore grid, a high voltage submarine cable with a lead sheath and steel amour may have to be used. The power generated by an offshore wind farm is transferred by the submarine cables buried in the seabed. The cables between the turbines are linked to a transformer substation, which, at most cases, will be placed offshore due to the long distance to shore, but for near shore wind farms (5 km or less from the shore) it may be placed onshore. Either oil-insulated cables or PEX-insulated cables can be used. The reactive power produced by the submarine cable connecting an offshore wind farm could be high, a 40 km long cable at 150 kV would produce around 100 Mvar [9], reactors may be needed to compensate the reactive power produced by the cable. For long distance transmission, the transmission capacity of the cables may be mainly occupied by the produced reactive power. In this situation high voltage direct current (HVDC) transmission techniques may be used. The new technology, voltage source converter based HVDC system, provides new possibilities for performing voltage regulation and improving dynamic stability of the wind farm as it is possible to control the reactive power of the wind farm and perhaps keep the voltage during a fault in the connected transmission systems.

### 2.2. Wind farm configurations

Large wind farms may present a significant power contribution to the grids, and play an important role in power system operation and control. Consequently, high technical demands are expected to be met by these generation units, such as frequency and voltage control, active and reactive power regulation, quick responses under power system transient and dynamic situations. The power electronic technology is an important part of the wind farms to fulfill these demands. Some possible electrical configurations of wind farms are shown in Fig. 3.

A wind farm equipped with DFIGs, is shown in Fig. 3(a), the power electronic converters can perform both active and reactive power control and operate the wind turbines in variable speed to maximize the captured energy as well as reduce the mechanical stress and noise. Such a system is in operation in Denmark as a 160 MW off-shore wind power station. Fig. 3(b) shows a wind farm with induction generators, a STATCOM or SVC can be used to provide the reactive power to meet the system reactive power and voltage control requirements.

For long distance transmission of power from an offshore wind farm, HVDC may be an interesting option. In a HVDC transmission, the low or medium AC voltage at the wind turbines/farms is converted into a DC voltage, the DC power is transferred to the onshore system, then it is converted back into AC power as shown in Fig. 3(c) and (d). The HVDC transmission system may be either the conventional thyristor based technology or the voltage source converter based technology. In Fig. 3(c), each wind turbine has its own power electronic converter, so it is possible for each wind turbine to operate at an individual optimal speed, while Fig. 3(d) shows a topology where wind turbines are connected as an AC network in the wind farm, therefore each wind turbine does not need a separated power electronic converter system.

There are also other possibilities, such as field excited synchronous machines or permanent magnet synchronous generators, which can be sued in the systems shown in Fig. 3(c) or Fig. 3(d), in the case of a multiple-pole generator, the multi-stage gearbox may be removed or replaced by a lower ratio gearbox. A comparison of the topologies is given in Table 1, where main features of various wind farms have been shown. The overall performance considerations will also include production, investment, maintenance and reliability, etc.

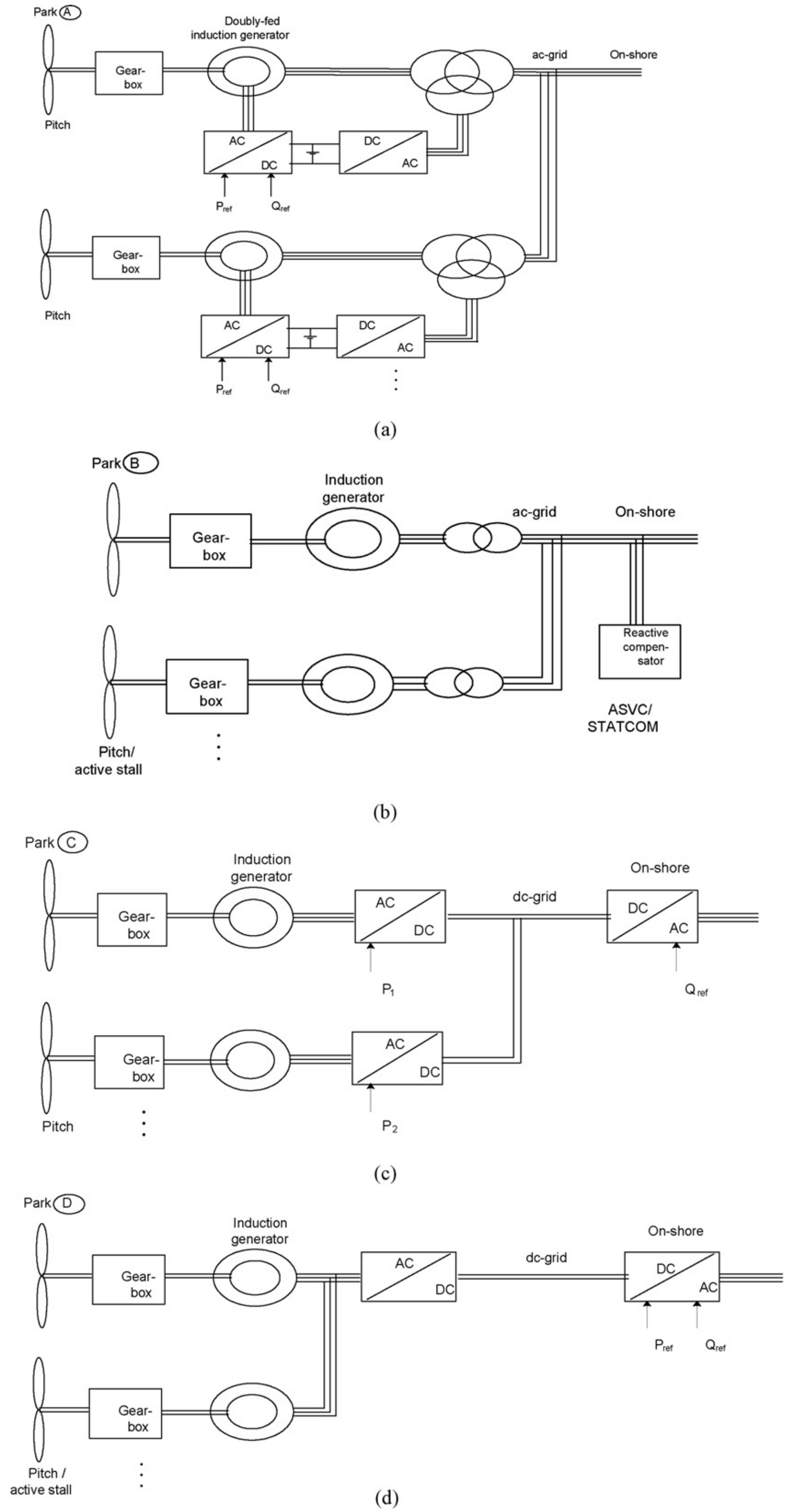
### 2.3. Development of offshore wind farms

Wind projects need a large area to achieve significant levels of energy production, however, it may not be easy to find suitable sites for land-based wind farms, while offshore wind farms have no such problems. Other advantage of moving turbines to offshore is that wind speed is more consistent and less turbulent, therefore more energy production and less wear and tear on turbines. Also offshore wind farms become more ubiquitous than that on land, so that placing wind farms offshore removes or minimizes the visual impact.

Meanwhile, wind turbine technology advances have made offshore wind farm increasingly attractive and financially viable. The basic technical requirements for efficient offshore wind turbine deployment are moderate wave heights, relatively shallow water, and "class 4 or 5" wind speeds, averaging 15.7 mph or higher [4]. The turbine technology and the actual construction of offshore wind farms are undergoing rapid progress as wind farms are planned to be erected in deeper waters and even further off the coast. Europe fortunately possesses all of those conditions in many offshore waters—making ideal offshore wind farm placement conditions.

**Table 1**
Comparison of four wind farm topologies [3].

| Farm configurations (Fig. 3) | A | B | C | D |
|---|---|---|---|---|
| Individual speed control | Yes | No | Yes | No |
| Control active power electronically | Yes | No | Yes | Yes |
| Control reactive power | Yes | Centralized | Yes | Yes |
| Short circuit (active) | Partly | Partly | Yes | Yes |
| Short-circuit power | Contribute | Contribute | No | No |
| Standby-function | Yes | No | Yes | Yes |
| Softstarter needs | No | Yes | No | No |
| Rolling capacity on grid | Yes | Partly | Yes | Yes |
| Investment | + | ++ | + | + |
| Maintenance | + | ++ | + | + |




a) Doubly-fed induction generator system with ac-grid

b) Induction generator with ac-grid

c) Speed controlled induction generator with common dc-bus and control of active and reactive power

d) Speed controlled induction generator with common ac-grid and dc transmission

**Fig. 3.** Wind farm configurations.

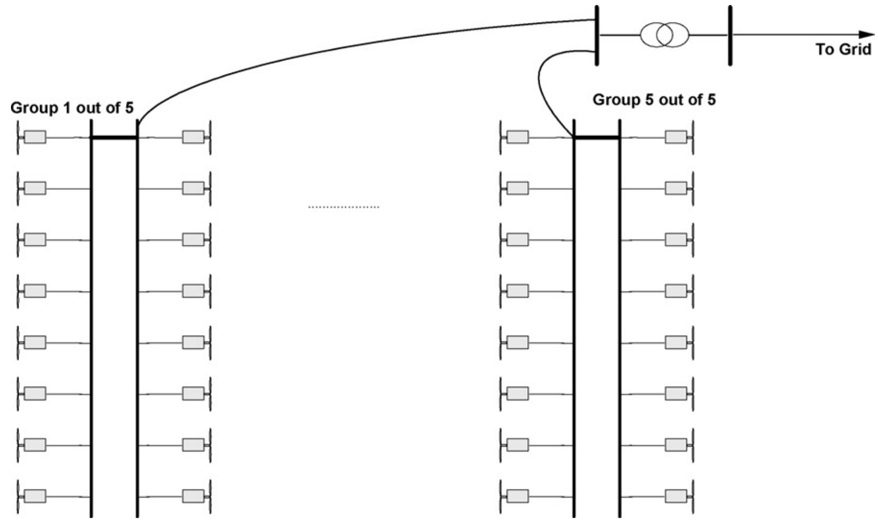



**Fig. 4.** Configuration of Danish Horns Rev offshore wind farm.

An offshore wind farm consists of almost the same components as an onshore wind farm; however, the harsh environment at sea may have more demands on the design and constructions. The operation and maintenance of an offshore wind farm depend greatly on the weather conditions which – in some seasons – will result in limited access to the turbines. Consequently, these activities become more time consuming and costly.

Offshore wind farms now account for about 2% of Europe's total wind capacity, Germany alone plans to have 3500 MW of offshore wind farms by 2010. It is expected that offshore turbines could be supplying 10,000 MW throughout Europe within five years.

## 3. Wind power in Denmark

### *3.1. Wind farms in Denmark*

Wind power development has a long history in Denmark. More than 3000 MW wind power is supplied by approximately 5500 wind turbines. The Danish government expects 5500 MW wind turbine capacity installed in Denmark by year 2030 including 4000 MW from offshore wind farms, which are expected to produce 13.5 TWh per year equivalent to 40% of the Danish electricity consumption [5].

Vindeby is the world's first offshore wind farm, which is located North of the island of Lolland in the Southern part of Denmark and was built by the utility company SEAS. Electricity production could be about 20% higher than comparable capacity wind farm on land. The most recent and largest offshore wind farms in Denmark are Horns Rev by the west coast of Jutland and Nysted close to Lolland [5,6]. Fig. 4 sketches the electrical connection of Horns Rev offshore wind farm which includes 80 wind turbines with doubly fed induction generators [8]. The Nysted Offshore Wind Farm consists of a total of 72 wind turbines. Table 2 lists some Danish offshore wind farms.

### *3.2. Wind power in Danish power systems [7]*

The total installed wind power in Denmark is very significant, considering the minimum and maximum loads of the system are 2000 MW and 6300 MW, respectively in 2004. There are periods when wind power generation may exceed power consumption. Such situations occur frequently in the western part of the country, where has the largest proportion of wind power penetration.

In Denmark most of the local wind turbines are fixed speed with conventional induction generators. Small wind turbines (below 0.5 MW) are being upgraded with larger and newer types of wind turbine systems, which will result in wind power generation further increase.

The Danish power systems are separated into Western Denmark power system and Eastern Denmark power system (no direct connection at present). In Western Denmark, the primary power plants are thermal, coal- or gas-fired units. A significant proportion of the power generation comes from local wind turbines and combined heat and power (CHP) units. The system has a large offshore wind farm, aforementioned Horns Rev A (HRA). In 2004, the installed wind power generation capacity corresponded to about 33% of the generation capacity of the area, whereas wind power covered about 22% of the electrical energy consumption of

**Table 2**
Danish offshore wind farms.

| Name | Year | Turbines | Distance from shore | Notes |
|---|---|---|---|---|
| Vindeby | 1991 | 11 Bonus 450 kW stall wind turbines | 1.5–3 km North of the coast of the island of Lolland | The world's first offshore wind farm |
| Tunø Knob | 1995 | 10 Vestas 500 kW pitch controlled | 3 km from the island of Tunø, and 6 km off the coast of the Jutland peninsula | The world's second offshore wind farm |
| Middelgrunden | 2000 | 20 Bonus 2 MW | 2 km off shore east of Copenhagen | The largest wind farm in the world based on cooperative ownership (2005) |
| Samsø | 2003 | 10 Bonus 2.3 MW | 3.5 km south of the island Samsø | Owned by local people, the island is fully supplied by renewable energy |
| Nysted | 2003 | 72 Bonus 2.3 MW | 10 km south of the town of Nysted on Lolland | The largest wind farm in Denmark in capacity (2005) |
| Horns Rev | 2002 | 80 Vestas 2 MW | 14–20 km off the coast of Jutland | The largest wind farm in Denmark in production (2005) |

Western Denmark. Western Denmark power system is interconnected through AC lines with Northern Germany system, where nuclear and thermal power plants are main generation units, also with rapidly growing wind power, and also through HVDC links to Norway and Sweden, where hydro power plants are the main generation units.

At present, most on-land sites with good wind conditions are already occupied by existing local wind turbines. The increase in the wind power in Western Denmark will come from large offshore wind farms and from upgrading of the small wind turbines with the newer, more efficient wind turbines rated at several MWs. This upgrading may contribute more than 300 MW to local wind power while the offshore wind farm, Horns Rev B (HRB) with a rated power of 200 MW is being built and expect to operate from 2009.

The primary power plants in Eastern Denmark are coal-fired. Eastern Denmark power system is interconnected through AC submarine cables to Sweden, the Nordel synchronous area. The offshore 165 MW wind farm at Nysted is connected to the 132 kV transmission system of Lolland. In 2004 the installed wind power corresponded to about 14% of the generation capacity of the area, whereas wind power covered about 12% of the electrical energy consumption of Eastern Denmark.

In Eastern Denmark, the increase of wind power in on-land sites may partly come from the upgrading of the existing small wind turbines, and partly from the use of new sites on the islands of Lolland and Falster where wind conditions are good. The main increase in the wind power in Eastern Denmark will come from the construction of new, large offshore wind farms. For example, Rødsand-2 with a rated power of 200 MW, has been announced by the Danish Energy Authority, and the completion is expected by the years 2008–2010.

## 4. Optimization of electrical system for offshore wind farms

Offshore wind farms are more expensive than onshore wind farms in both installation and maintenance. Intensive research and technology development make various offshore wind farm configurations possible, which may lead to different costs, reliability, power quality, and system efficiency. Thus, the optimization of the electrical system design for offshore wind farms becomes important.

A project has been conducted at Aalborg University on the Optimization of Electrical System for Offshore Wind Farms [8]. The two main tasks of this project are: (1) develop an algorithm for finding the grid acceptable capacity of an offshore wind farm; (2) optimize the electrical system of the offshore wind farm.

The capacity of a grid connected wind farm may be limited by the capability of the grid system. A method combined with probabilistic analysis has been developed to obtain the maximum possible capacity for a given wind farm site. The thermal limit of the transmission lines, the voltage stability, the limitation of Load Tap Change (LTC) transformers, and the power generation limits are considered as the constraint conditions.

The optimization platform with the main structure shown in Fig. 5 [8] has been developed. The optimization is implemented with a Genetic Algorithm (GA). Various GA techniques are investigated to improve the optimization performance. The platform is based on a knowledge database, and composed of several functional modules such as cost calculation, reliability evaluation, loss calculation, AC–DC integrated load flow algorithm, etc. The objective of the optimization is to minimize the Levelized Production Cost (LPC) with a reliability index taken into account. LPC is the discounted life-cycle average cost per unit of electricity produced. It considers the capital costs, the maintenance costs, the power losses and power generation. A new reliability index, Loss of Generation Ratio Probability (LOGRP), is proposed to evaluate the electrical system [9].

This work also proposes a serial AC–DC integrated load flow algorithm for variable speed offshore wind farms. The model of DC/DC converters is proposed and integrated into the basic DC load flow algorithm by modifying the Jacobian matrix. Two iteration methods are developed to respectively take into account the control strategy and power losses of power electronic converters [10].

The developed optimization platform has been applied to real offshore wind farms, and satisfactory results are obtained. One of the examples is briefed as follows.

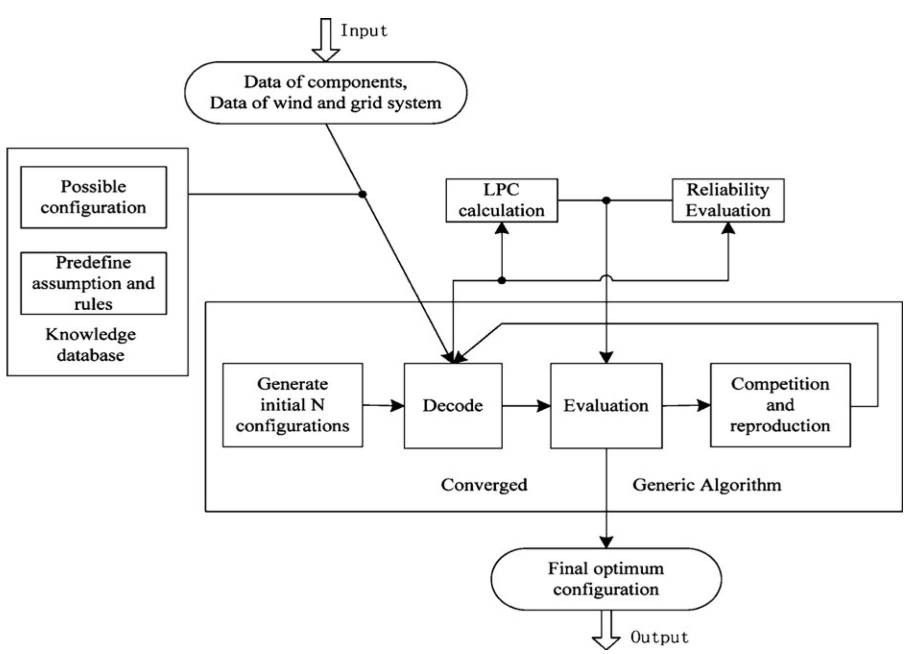



**Fig. 5.** Main structure of the optimization platform [8].

The wind farm would be 6 km away from the shore and would have 60 wind turbines to be installed. The geographic position of each WT is fixed based on the wind direction and seabed condition. The cost of the offshore platform is related to the capacity and is estimated based on existing projects.

The following conditions are to be considered

- Wind turbine type options (3 MW, 3.6 MW, 4.5 MW and 5 MW)
- Possible voltage levels of PCC (either 132 kV or 400 kV)
- The costs for cables (including the installation cost)
- The way of configuring clusters (such as number of turbines per cluster)

The datasheet required for the optimization of the wind farm include the following items:

- Wind speed distribution
- Datasheet of possible types of WT which include the power curve, rated voltage, costs and availability parameters
- Datasheet of possible types of marine cables
- Datasheet of possible types of land cables
- Datasheet of possible types of transformers

A database is constructed to specify all the datasheets for the optimization procedure.

The search space of the optimization is quite big, and the chosen essential GA parameters for the optimization are summarized as follows:

- Initial population: random generation with diversity check
- Selection operator: Niching method
- Crossover operator: uniform crossover
- Mutation operator: non-uniform mutation

The GA is converged after 85 generations. The obtained key optimal design parameters are listed in Table 3. The single line diagram of the optimal design is shown in Fig. 6.

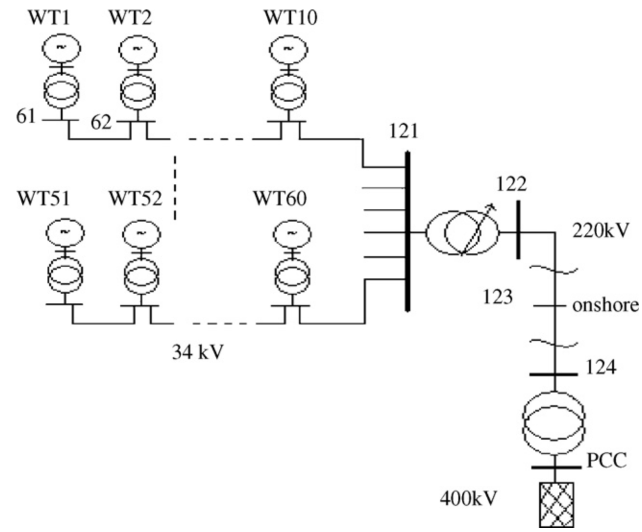



**Fig. 6.** Single line diagram of the optimal design for the large wind farm [8].

## 5. Operation and control wind farms of in grid

Integration of large scale wind power may have severe impacts on the power system operation. Stable, reliable and economic operation of the power system under the massive integration of wind power is a big challenge to power system operators. The technical specifications, grid codes, for grid connection of wind turbines (the large offshore wind farms to the high-voltage transmission networks as well as the local wind turbines to the distribution networks) have been produced to specify the requirements that wind turbines must meet in order to be connected to the grid. Examples on such requirements include capabilities of contributing to frequency and voltage regulation by continuously controlling the active power and reactive power supplied to the power system, and the low voltage ride-through capability.

Some typical specifications are listed as follows.

Active power and frequency control: the active power is regulated linearly with frequency variation between a certain range (47–52 Hz) with a dead band (49.85–50.15 Hz) and the regulating speed is 10% of the rated power per second. The regulation ability of reducing the wind turbine production from full load to a level between 0 and 20% in a few seconds is required.

- The reactive power should be regulated within a control band, at a maximum level of 10% of rated power (absorption at zero active power and production at the rated active power);
- Wind turbine will generally operate in normal conditions (90–105% voltage and 49–51 Hz), however, it may also be allowed to operate outside of the above conditions within specified time limits;
- Under the condition of a power system fault, a wind turbine would experience a voltage variation. The severity of the voltage variation and the time period of such voltage variation will determine whether the wind turbine must not be disconnected (low voltage ride through) or may be disconnected or must be disconnected;

  Also the wind turbine has to be able to withstand more than one independent faults occurred in a few minute intervals.

There are also requirements related to rapid voltage variations, flickers, harmonics and interharmonics.

The main impacts of wind turbine integration on power systems and the possible methods of realizing good security and power quality for the power systems integrated with large scale wind power are to be discussed with the following issues:

- Power balance control
- Voltage fluctuation and quality
- Low voltage ride-through capability

**Table 3**
Description of the main optimal design parameters for the large wind farm.

| Optimization variables | Optimal values |
|---|---|
| Selection of wind turbine | 4.5 MW |
| Type of clustering | String clustering without redundancy |
| Number of clusters | 6 |
| Transmission system | AC, 1 SCC |
| Voltage level | 34 kV/220 kV/400 kV |
| Selection of ICC | 34 kV, 3*95/3*300/3*800 $mm^2$ |
| Selection of SCC | |
| Offshore | 250 kV, 3*630 $mm^2$ |
| Onshore | 250 kV, 1*800 $mm^2$ |
| Selection of offshore transformer | 1 offshore platform, 300 MVA, 224/34 kV |
| Selection of onshore transformer | 1 substation, 300 MVA, 400/224 kV (with tap changer) |

### 5.1. Power balance control

The wind power penetration levels is increasing, for example, average wind power penetration levels of 20–30% with peak penetration level up to 100% of the system load as aforementioned in Denmark. Wind farms' productivity fluctuates with the wind speed, while the electrical grid must maintain a balance between the supply and the demand. The effects of fluctuating wind power on system regulation and stability are very important issues.

Large offshore wind farms may inject significant power fluctuations into power systems, such power fluctuations may affect neighboring power systems if not be appropriately controlled. For example, the offshore wind farm Horns Rev A in Western Denmark produces more intense active power fluctuations than the aggregated wind power produced by land-based wind farms in the system and shows frequent active power fluctuations within periods of tens of minutes, the power gradients may reach 15 MW per minute, thus the 160 MW wind farm could have the output power change between zero and the rated power in 10–15 min [7]. The system power balance could also be worsen by the deviations from the planned power exchange between Norway and Sweden (two DC links). The total power fluctuations and deviations would be seen in deviations of the power exchange between Western Denmark and the northern Germany, UCTE synchronous area.

Expansion of wind power means additional demands on regulating power. In order to keep a power system in stable operation within the specified frequency range, the active power supplied by the generation units, including energy storage devices, must be adjusted continuously to match the varying load in the system. Such a power balance need to consider all power exchanges related to the concerned area, for example, the deviations from the scheduled power exchange between neighboring areas. However, wind power is characterized by fluctuations due to the fluctuating nature of wind speed, the active power generation of a wind turbine can be regulated down from the available power based on the wind speed at the time but it may be difficult to increase the power output since the available input power is limited by the wind speed. The larger scale the wind power integration, the more serious the wind power fluctuation, consequently, it would be more difficult to keep the system power balance within the specified frequency range.

From the system operator's point view, a system level hot reserve allocation among the generation units may be more cost effective to deal with the problem if possible. Optimization of regulating and reserve power will enable the cost effective utilization of the capacity of the available generation units. Such optimization would depend on forecast accuracy of wind power and market structure. It is important to forecast the wind speed so as to estimate the amount of power generation from the wind farms, which will be used to help the planning and scheduling to meet system loads and contractual agreements. If the installed wind power capacity is large, then, a small error in the wind forecast could results in a significant error in the active power prediction. Accurate wind speed forecast would enable to maximize profits and minimize risks.

An Area Grid Controller (AGC) [7] with the secondary control applied on the central power plants and links to other neighboring power systems, including the HVDC connections, can be used to deal with the wind power fluctuations. The use of the fast power control of the HVDC systems will be very effective for keeping the power deviations within the desired range. Obviously, larger wind power penetration, especially, from the centralized wind farms, such as offshore wind farms, will demand higher regulating abilities of the power system.

Local CHPs, though small in capacity of each unit, may play an important role if large number of such units exists in a power system, like the Danish power system. Those CHP units may contribute to the power balance of the power system and can participate in the power market.

Large scale energy storage system may present an answer, some fast response energy storage devices could be well technically suited for this purpose though more work is needed to make the solution an economic one [11]. Heat storage systems can also contribute, since the storage system could decouple the heat production and power production, therefore to give more freedom for CHPs (large thermal units or small local units) to perform power balance control.

Wind farm may actively participate in grid management, including provision of regulating power and generation management. In order to deal with large scale power fluctuations, some spinning reserve may have to be kept in wind turbines. In this case, the wind turbine may have to operate at a lower power level than the available power level, which means a reduced utilization of the fuel free energy, a reduction in generation, and hence reduced revenues.

In order to deal with the power balance, the power system may need sufficient amount of regulating power, the appropriate arrangements of power exchange with neighboring power systems could also ease the task.

In summary, power balance issue can be dealt with several methods, such as

- Improvement of the forecast of wind speed and power;
- Provision of regulating and reserve power from other generation units (main power station and CHPs);
- Load management of selected consumers;
- Provision of regulating and reserve power from large wind turbines/farms;
- Application of energy storage technologies;
- Establishment of appropriate power exchange agreements to utilize the regulating power control in neighboring power systems.

### 5.2. Voltage fluctuations

Voltage variation is a major problem associated with wind power. This can be a limiting factor on the amount of allowed wind power to be installed. Wind turbines equipped with induction generators consume reactive power. At no load (idling), the reactive power consumption is about 35–40% of the rated active power, and increases to around 60% at the rated power. Reactive power is one of the major causes of voltage instability in the network, it also contributes to power losses.

In normal operational condition, the voltage quality of a wind turbine or a group of wind turbines may be assessed in terms of the following parameters [12]:

- Steady state voltage under continuous production of power
- Voltage flickers
  - Flicker during operation
  - Flicker due to switching

The influence of connecting a wind farm on the gird voltage is directly related to the short-circuit capacity. The short-circuit capacity at a given point in the electrical network represents the system strength. If the voltage at a remote point can be taken as constant, $U_s$, and the short-circuit capacity (SCC) in MVA is defined as $U_S^2/Z_k$ where $Z_k$ is the equivalent impedance between the points concerned.

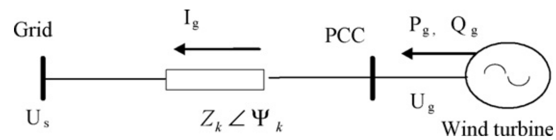



**Fig. 7.** A simple system with an equivalent wind power generator connected to a network.

Fig. 7 illustrates an equivalent wind power generation unit, connected to a network with equivalent short-circuit impedance, $Z_k$. The network voltage at the assumed infinite busbar and the voltage at the Point of Common Coupling (PCC) are $U_s$ and $U_g$, respectively. The output power and reactive power of the generation unit are $P_g$ and $Q_g$, which corresponds to a current $I_g$.

$$I_g = \left(\frac{S_g}{U_g}\right)^* = \frac{P_g - jQ_g}{U_s} \tag{1}$$

The voltage difference, $\Delta U$, between the system and the connection point is given by

$$\begin{aligned} U_g - U_s = \Delta U = Z_k I_g = (R_k + jX_k)\left(\frac{P_g - jQ_g}{U_g}\right) \\ = \frac{R_k P_g + X_k Q_g}{U_g} + j\frac{P_g X_k - Q_g R_k}{U_g} = \Delta U_p + j\Delta U_q \\ \approx \frac{R_k P_g + X_k Q_g}{U_g} \end{aligned} \tag{2}$$

The voltage difference, $\Delta U$, is related to the short-circuit impedance, the active and reactive power output of the wind power generation unit. It is clear that the variations of the generated power will result in the variations of the voltage at PCC. If the impedance $Z_k$ is small (the grid is strong) then the voltage variations will be small. On the other hand, if $Z_k$ is large (the grid is weak), then the voltage variations will be large.

*5.2.1. Voltage control by reactive power*

Voltage is closely related with the reactive power as shown in (2), thus the wind turbines with the ability of controlling reactive power can support system voltage control. The modern large wind farms are required to have the ability of controlling both active and reactive power. In the case of the fixed speed wind turbines with conventional induction generators, the reactive power may be controlled by thyristor-switched capacitor banks. Furthermore, a dynamic reactive power control unit may additionally be installed at Point of Common Coupling (PCC). In the case of power electronic converter based wind turbines, such as those with doubly fed induction generators or with full-rated power electronic converters, the reactive power control can be performed by the converters. Consequently, significant active power fluctuations from the wind speed variations may not lead to corresponding fluctuations of the grid voltage at the connection point of the wind farm. One of such case is Horns Rev offshore wind farm equipped with DFIGs.

For the wind farm with the fixed speed wind turbines equipped with conventional induction generators, the active power production and the reactive power absorption are strongly coupled, such as the grid of Eastern Denmark. Thus, the active power fluctuations may result in similar fluctuations of the reactive power absorption, and if appropriate dynamic reactive power compensation equipment is not in place, the voltage fluctuations may be quite significant.

Locally installed capacitor banks may compensate the reactive power demand of the induction generators. For WT with self commutated power electronic systems, the reactive power can be controlled to minimize losses and to increase voltage stability. For a large scale wind farm, a central reactive power compensation device, such as SVC or STATCOM may be used to provide a smooth reactive power regulation [11].

*5.2.2. Voltage flickers*

Fluctuations in the system voltage (more specifically in its rms value) may cause perceptible light flicker depending on the magnitude and frequency of the fluctuation. This type of disturbance is called voltage flicker, or shortened as flicker.

There are two types of flicker emissions associated with wind turbines, the flicker emission during continuous operation and the flicker emission due to generator and capacitor switchings. Often, one or the other will be predominant. The allowable flicker limits are generally established by individual utilities. Rapid variations in the power output from a wind turbine, such as generator switching and capacitor switching, can also result in variations in the RMS value of the voltage. At certain rate and magnitude, the variations cause flickering of the electric light. In order to prevent flicker emission from impairing the voltage quality, the operation of the generation units should not cause excessive voltage flicker.

IEC 61000-4-15 specifies a flickermeter which can be used to measure flicker directly [13]. The flicker measurement is based on a "flicker algorithm" to calculate the $P_{st}$ and $P_{lt}$, where $P_{st}$ is the short term flicker severity factor and measured over 10 min, and the long term flicker severity factor $P_{lt}$. is defined for 2-h periods. The flicker study may be conducted with simulation method [14]. Also the flicker emissions, $P_{st}$ and $P_{lt}$ may be estimated with the coefficient and factors, $c_f(\Psi_k, v_a)$ and $k_f(\Psi_k)$ obtained from the measurements, which are usually provided by wind turbine manufacturers.

The flicker emissions from a wind turbine installation should be limited to comply with the flicker emission limits. It is recommended [15] that $P_{lt} \leq 0.50$ in 10–20 kV networks and $P_{lt} \leq 0.35$ in 50–60 kV networks are considered acceptable. However, different utilities may have different flicker emission limits.

*5.2.3. Harmonics*

Harmonic disturbances are a phenomenon associated with the distortion of the fundamental sine wave and are produced by non-linearity of electrical equipment. Harmonics causes increased currents, power losses and possible destructive overheating in equipment. Harmonics may also rise problems in communication and control systems. Harmonic standards are specified to set up the limits on the Total Harmonic Distortion (THD) as well as on the individual harmonics.

Power electronic converters, which operating in an on-and-off way, are used in variable speed wind turbine systems. The Pulse Width Modulation (PWM) switching strategy, with a typical switching frequency of a few thousand Hz, shifts the harmonics to higher frequencies where the harmonics can be easily removed by smaller filters. In general, harmonic standards can be met by modern wind turbines.

*5.3. Wind turbines in power system transients-low voltage ride-through capability and stability support*

An important issue when integrating large scale wind farms is the impacts on the system stability and transient behavior. The low voltage ride-through capability of the large offshore wind farms is very relevant issues for system stability.

System stability is largely associated with power system faults in a network such as tripping of transmission lines, loss of production capacity (generator unit failure) and short circuits.

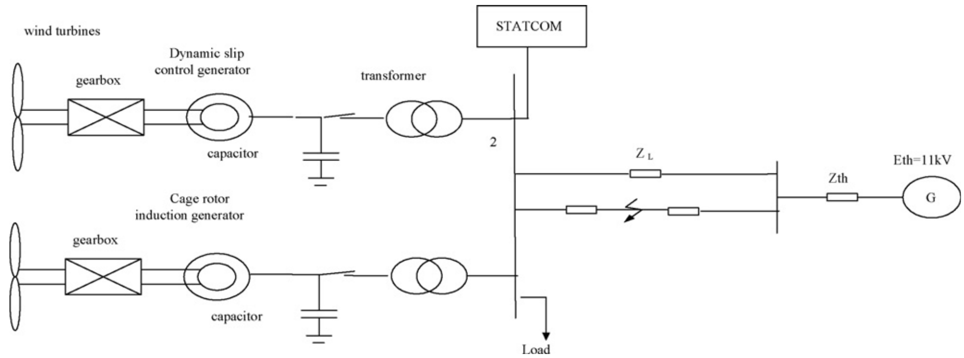



**Fig. 8.** Block diagram of a wind power conversion system connected to a grid.

These failures disrupt the balance of power (active and reactive) and change the power flow. Though the capacity of the operating generators may be adequate, large voltage drops may occur suddenly. The unbalance and re-distribution of active and reactive power in the network may force the voltage to vary beyond the boundary of stability. A period of low voltage (brownout) may occur and possibly be followed by a complete loss of power (blackout).

Many power system faults are cleared by relay protections of the power system either by disconnection or by disconnection plus fast reclosure. In all the situations the result is a short period of low or no voltage followed by a period of voltage recovering. A wind farm nearby will see this event. In early days when only a few wind turbines were connected to the grid, if a fault somewhere in the lines caused a voltage drop at the wind turbine, the wind turbine was simply disconnected from the grid and would be reconnected again when the fault was cleared and the voltage returned to normal. Because the penetration of wind power in the early days was low, the sudden disconnection of a wind turbine or even a wind farm from the grid did not cause a significant impact on the stability of the power system. With the increasing penetration of wind energy, the contribution of power generated by wind farms can be significant. If the entire wind farm is suddenly disconnected at full-rated operation, the power system will loss further production capability. Unless the remaining operating power plants have enough "spinning reserve", to replace the lost power within very short time, a large power disturbance may occur and possibly followed by complete loss of power. Therefore, modern wind turbines/farms are required to be connected to the grid or "ride through" during disturbances and faults. A lot of work has been done on the system dynamic studies related to the "low voltage ride through" [16–26].

In order to keep the system stability, it is necessary to ensure that the wind turbine restores normal operation within a required time. Different methods may be used for different types of wind turbine technologies, which may include supporting the system voltage with reactive power compensation devices, and keeping the generator at appropriate speed by regulating the power, etc. [22–26].

### *5.3.1. A simulation example*

A series of simulation studies are shown in this section. The studied system is shown in Fig. 8, where stall regulated wind turbines are connected (one rotor short-circuited induction generator and one dynamic slip controlled wound rotor induction generator). A load at Busbar 2 is supplied by the wind power generators and the external power system which is represented by a constant voltage source connected in series with its Thevenin's equivalent impedance. The capacitors at the wind generator terminal supply the reactive power required by the generators, the STATCOM may also supply a part of reactive power. The voltage drop is caused by a three-phase to ground short-circuit fault at the middle of one of the two parallel lines as shown in Fig. 8. It begins at 2 s and the line is tripped after 250 ms.

A few studied cases are presented in this paper. The results show the speed, torque, voltage and current of the generators, and the reactive power provided by STATCOM.

**Case 1.** One rotor short-circuited induction generator in operation without a STATCOM

The fault causes a reduction of the electromagnetic torque on the induction generator, consequently, the generator is accelerating. After the fault is cleared, the system voltage intends to recovery, however, the generator takes large amount of reactive power in order to re-establish the magnetic field, which results in a lower voltage and lower electromagnetic torque. In this case, the generators will keep accelerating until cut off by the protection devices. The generator system is not stable. The results are shown in Fig. 9.

**Case 2.** One rotor short-circuited induction generator with a STATCOM in operation

This case is similar to Case 1 except the STATCOM is in operation. The simulation results are shown in Fig. 10. It can be seen that the terminal voltage can be restored with the STATCOM. The torques are balanced and the induction generator can restore normal operation.

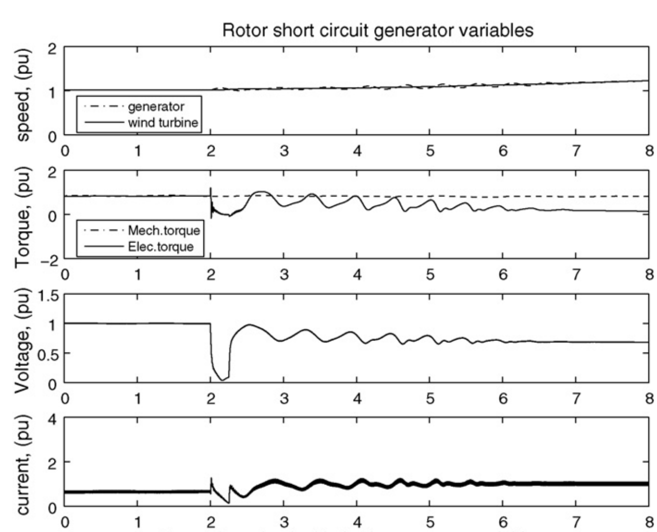
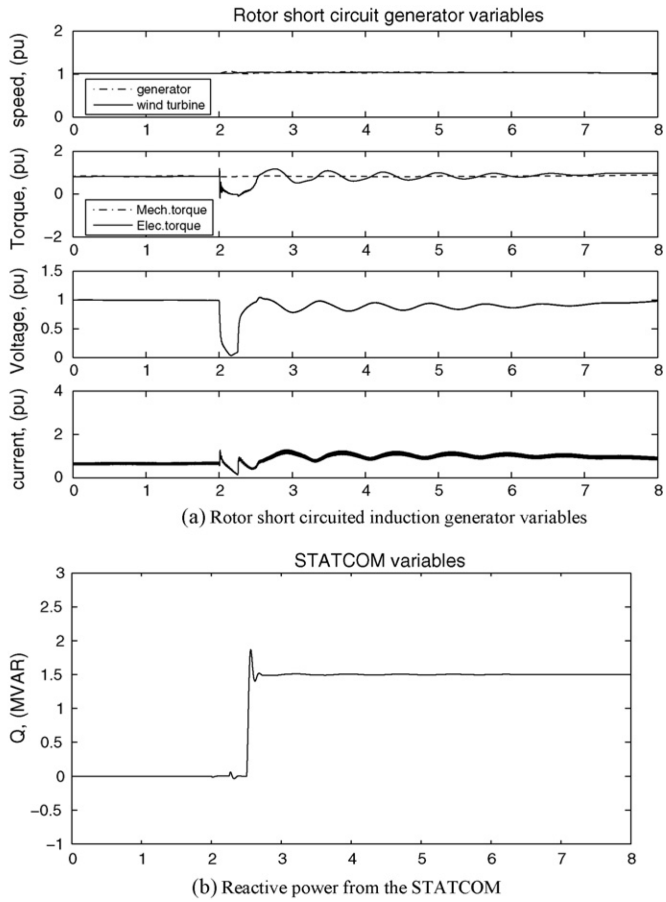



**Fig. 9.** Simulation results of a cage rotor induction generator without STATCOM.




(a) Rotor short circuited induction generator variables

(b) Reactive power from the STATCOM

**Fig. 10.** Simulation results of a cage rotor induction with STATCOM.

**Case 3.** One rotor resistance controlled induction generator with a STATCOM in operation

This case is similar to Case 2 but the generator is replaced with a rotor resistance controlled induction generator, which is under a normal dynamic slip control without equivalent resistance variation during the fault. The simulation results are shown in Fig. 11. The STATCOM operates in the same way as shown in Fig. 10(b). It can be see generator is stable, and the torque and speed variation are smaller than that in Case 2.

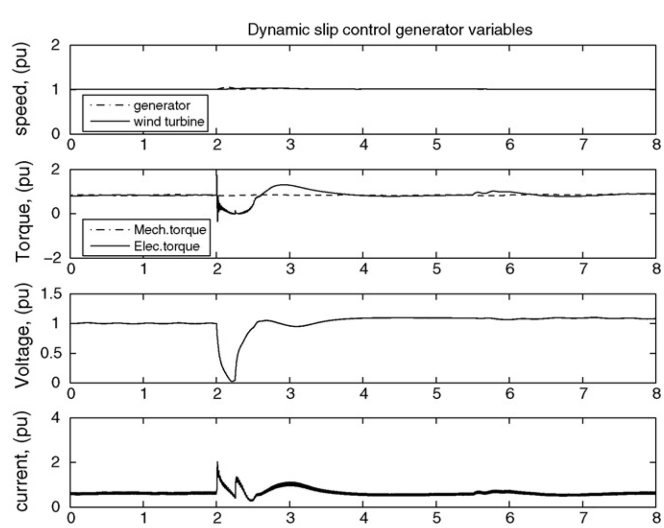


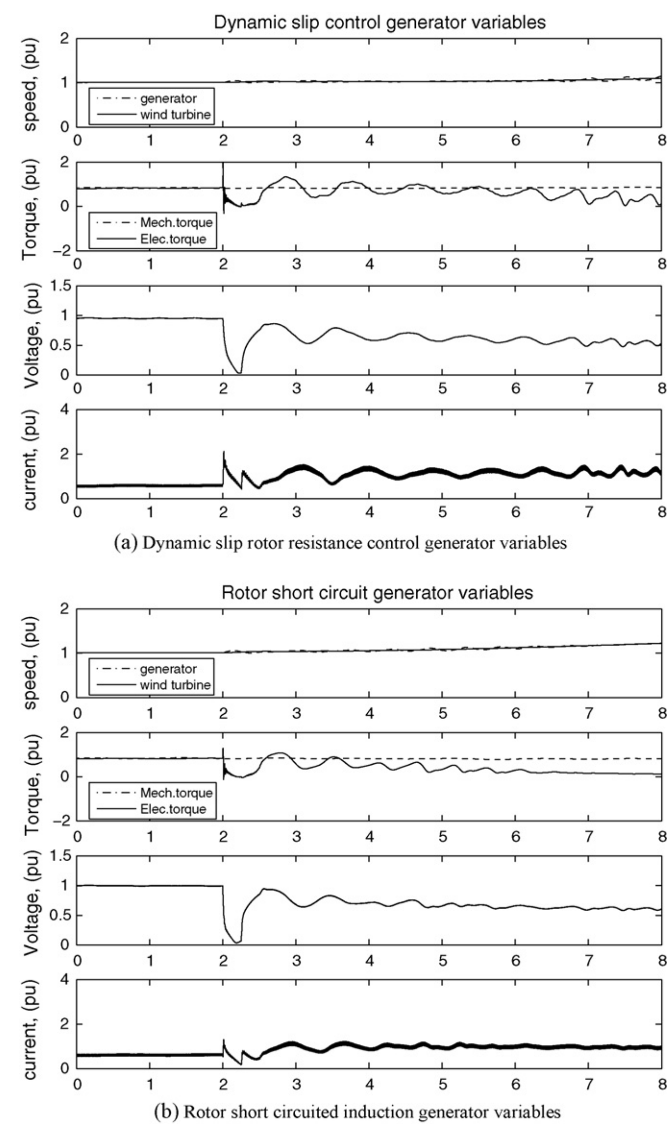

**Fig. 11.** Simulation results of a dynamic slip rotor controlled induction generator with STATCOM.

**Case 4.** Both the rotor short-circuited induction generator and the rotor resistance controlled induction generator in operation with a STATCOM

In this case studies, both the generators in Case 2 and in Case 3 (the rotor resistance controlled induction generator without change of the equivalent resistance during the fault) are connected in parallel operation, and the STATCOM operates in the same way as shown in Fig. 10(b). The simulation results are shown in Fig. 12. It can be seen the generators are unstable. The reason is more reactive power is absorbed by the two generators during the low voltage period, which causes further voltage drop during the recovery, and makes the ride through even more difficulty.

**Case 5.** Both the rotor short-circuited induction generator and the rotor resistance controlled induction generator in operation with a STATCOM and the rotor resistance control

In this case study, the conditions are similar to that in Case 4, except that the equivalent resistance of the rotor resistance




(a) Dynamic slip rotor resistance control generator variables

(b) Rotor short circuited induction generator variables

**Fig. 12.** Simulation results of two generators with STATCOM, (equivalent rotor resistance has not been changed during the fault).

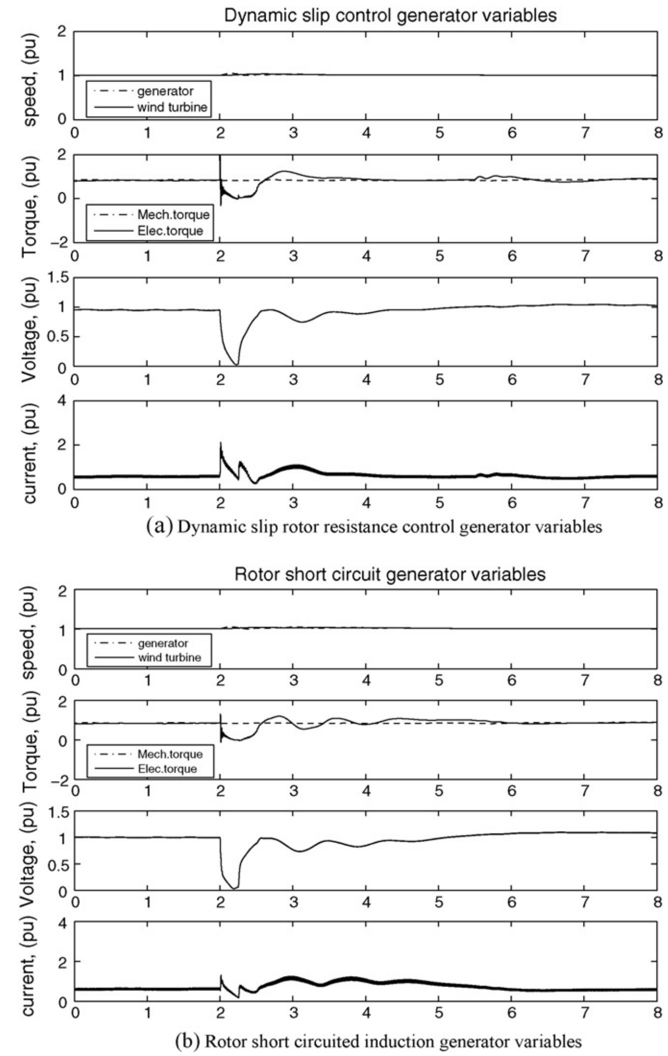



**Fig. 13.** Simulation results of two generators with STATCOM (equivalent rotor resistance has been changed during the fault).

controlled induction generator has been changed during the fault. Such a control changes the torque characteristics of the generator and improves the torque balance. The STATCOM operates in the same way as shown in Fig. 10(b). The simulation results are shown in Fig. 13. It can be seen the generators are stable. It has demonstrated that the rotor resistance control is an effective way to improve stability.

It is clear that the main methods of improving stability are reactive power control to keep good voltage level and torque/active power control to limit the over-speed of the generator. Therefore, an appropriate control strategy may include the following.

- Enhance reactive power supply to restore system voltage, such as with a STATCOM
- Limit generator speed by controlling the torque, with pitch control or dynamic slip control (rotor equivalent resistance)

Other methods may include reducing the reactive power consumption by disconnecting some induction generators, for example, the generators without means of actively regulating the torque may be disconnected to reduce the reactive power consumption, in order to recover other wind turbines with the ability of regulating torque first.

## 6. Conclusions

Wind power industry has been developing rapidly, and high penetration of wind power into grid is taking place. Integration of large scale wind power into power systems presents many new challenges. The largest increase of grid connected wind power is expected to come from large wind farms. Wind turbines/farms may be required to have good controllability similar to conventional power stations. The paper presents the modern wind turbines/farms and describes the Danish wind power status. An offshore wind farm optimization platform is briefed. The impacts and behaviors of large scale wind power on power system operation, power quality, and power system stability are described, further more, the possible technical methods of dealing with the challenges are discusses.

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**Zhe Chen** (M'95, SM'98) received the B.Eng. and M.Sc. degrees from Northeast China Institute of Electric Power Engineering, Jilin City, China, and the Ph.D. degree from University of Durham, U.K. He was a Lecturer and then a Senior Lecturer with De Montfort University, U.K. Since 2002, Dr. Chen became a Research Professor and is now a Professor with the Institute of Energy Technology, Aalborg University, Denmark. His background areas are power systems, power electronics and electric machines; and his main current research areas are renewable energy and modern power systems. Dr Chen has more than 180 publications in his technical field. He is an Associate Editor of the IEEE Transactions on Power Electronics, a Member of the Institution of Engineering and Technology (London, U.K.), and a Chartered Engineer in the U.K.

**Frede Blaabjerg** (S'86-M'88-SM'97-F'3) received the M.Sc.EE. from Aalborg University, Denmark in 1987, and the Ph.D. degree from the Institute of Energy Technology, Aalborg University, in 1995. He was employed at ABB-Scandia, Randers, from 1987 to 1988. During 1988 to 1992 he was a Ph.D. student at Aalborg University. He became an Assistant Professor in 1992 at Aalborg University, in 1996 Associate Professor and in 1998 full professor in power electronics and drives the same place. His research areas are in power electronics, static power converters, AC drives, switched reluctance drives, modeling, characterization of power semiconductor devices and simulation, wind turbines and green power inverter. He is the author or co-author of more than 300 publications in his research fields. During the last years he has held a number of chairman positions in research policy and research funding bodies in Denmark. He is the Editor in Chief, IEEE Transactions on Power Electronics, and associate editors for many other journals.